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Net Phytoplankton of the Ala Wai Canal, O'ahu, Hawai'i[1]

KEVIN S. BEACH,[2] ROBERT HARRIS,[3] MICHELLE HOLSOMBACK,[3] MELISSA RABAGO,[3] AND CELIA M. SMITH[2]

ABSTRACT: The Ala Wai Canal currently possesses a diverse and differentially distributed phytoplankton community that includes a minimum of 20 diatom genera, four dinoflagellate genera, and one cyanophyte genus. The diatom populations of the canal may be characterized by two ecological components: (1) diatoms thought to be intolerant of the estuary's variable physical conditions, and (2) diatoms believed to be tolerant to most environmental conditions found in the canal. The phytoplankton in the region between the head of the Ala Wai Canal and the Mānoa-Pālolo Stream outfall are primarily dinoflagellates. These algae may be restricted to this part of the canal, in part, because the sediment berm formed adjacent to the Mānoa-Pālolo Stream outfall restricts water motion, thereby altering circulation patterns, water temperature, and oxygen concentration at the head of the canal, favoring a dinoflagellate dominated-community. *Lyngbya* (Cyanophyta) is found throughout the canal at low relative densities. The distribution of the dominant diatom *Skeletonema costatum* (Greville) Cleve as well as similarity of phytoplankton populations across sites indicated that migration of phytoplankton within the canal is tidally controlled. Flushing the canal by pumping in seawater at its head has the potential to substantially alter phytoplankton composition and distribution at points in this waterway and may eliminate an entire division of algae from the head of the canal.

AT THE TIME THE Ala Wai Canal was constructed by the Army Corps of Engineers in 1927, little was known of the coastal phytoplankton around O'ahu. This man-made estuary was originally designed to drain the low-lying wetlands of Waikīkī (Miller 1975) and thus altered usual stream discharge patterns and created an artificial body ca. 3200 m long with an average depth of 2.0 m (with much variation) for phytoplankton growth. A shallow sediment berm at the Mānoa-Pālolo Stream outfall restricts water movement in the east end of the canal (Laws et al. 1993), potentially setting up two regions for phytoplankton distribution.

Historical studies of the Ala Wai Canal include aspects of its physical oceanography (Gonzalez 1971), rates of primary productivity (Harris 1975, Laws et al. 1993), phytoplankton distribution based on pigment determinations (Laws et al. 1994), and faunal components (Miller 1975). Patterns reported from the literature include peak primary production during April through July (Harris 1975) and gross photosynthetic rates increasing by a factor of three from the mouth to the head of the estuary (Laws et al. 1993). High productivity indices have been detected at the Ala Wai Yacht Harbor (the mouth) and were speculated to correlate with varying species composition across the canal (Harris 1975). Differential distributions were attributed to a high rate of flushing at the mouth of the canal (Harris 1975). Those results were further substantiated by the pigment-based

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[2] Department of Botany, University of Hawai'i at Mānoa, 3190 Maile Way, Honolulu, Hawai'i 96822.

[3] NSF Young Scholars Program participants, summer 1992.

differences in the distribution of the phytoplankton divisions in the Ala Wai Canal (Laws et al. 1994). Overall diatom and dinoflagellate distributions were segregated vertically and horizontally in the waters of the canal; diatoms dominated at the mouth of the canal, and dinoflagellates dominated at the head of the canal as judged by marker pigments. Oxygen concentrations near the head of the canal showed a marked reduction attributable to the restricted circulation (Miller 1975).

Clearly, the distribution of phytoplankton division-specific pigments, primary productivity indices, and physical parameters of the Ala Wai Canal suggest that the canal may support a diverse and regionally structured phytoplankton assemblage. To date, a thorough description of primary producers in the Ala Wai Canal remains incomplete in terms of phytoplankton identities, abundance, and distribution. This study documents the common genera of phytoplankton found in the water of the Ala Wai Canal, examines the effect of a tidal cycle on their distribution, and proposes some of the possible changes that may take place in community structure if flushing of the canal is carried out as has been proposed (Cox and Miller 1976).

MATERIALS AND METHODS

Field Collection

Net plankton samples were collected at six different sites along the Ala Wai Canal in Honolulu during the summer of 1992 (Figure 1). A plankton net (9.0-μm mesh) was towed for 10 m, sampling a 0.314-m^3 body of subsurface water. The plankton net was rinsed with 0.2 μm filtered seawater and the sample concentrated to an approximate total volume of 100 ml. Samples were immediately preserved in 4% buffered formalin. Three replicate samples were taken each day at each site during low, high, and flood tides on 25 June (+0.183 m flood tide), 30 June (−0.091

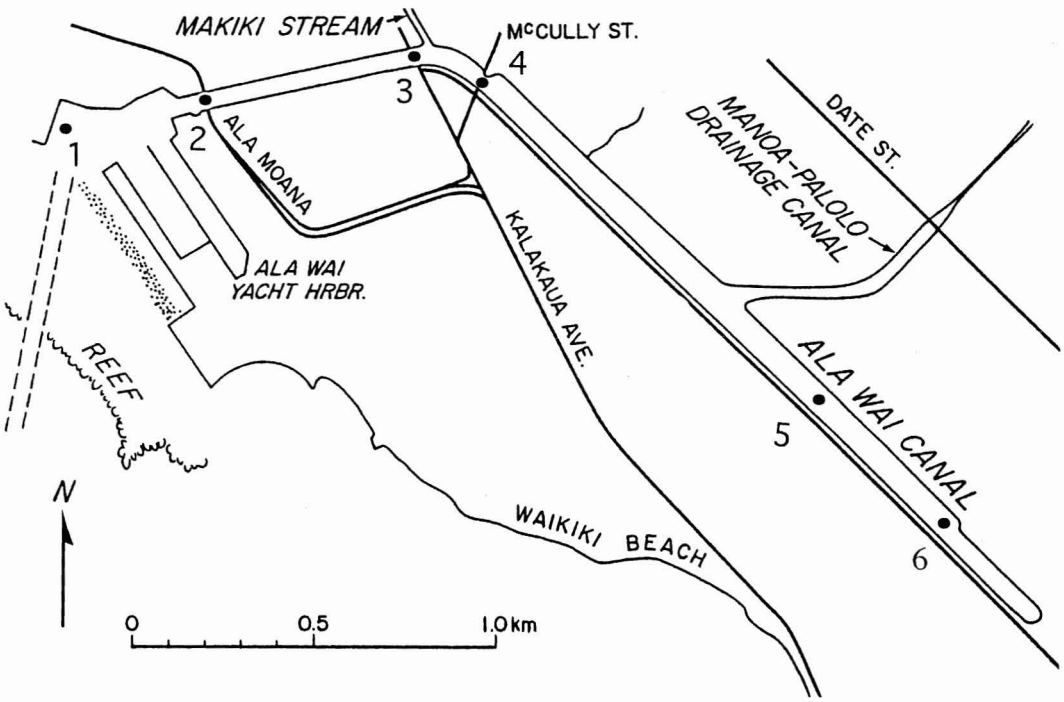

FIGURE 1. Sampling sites along the Ala Wai Canal (modified from Laws et al. 1993).

m low tide), 7 July (+0.518 m high tide), and 14 July (−0.061 m low tide). Samples were not collected from sites 5 and 6 during flood tide.

Laboratory Analysis

Low-spin centrifugation for 5 min in a tabletop centrifuge further concentrated plankton samples. After a thorough mixing of the condensed sample, microscope slides were prepared from random 0.25-ml aliquots and evaluated using a microscope (Nikon Labophot-2) at 100 × and 400 × total magnification under phase contrast. The net phytoplankton within four randomly chosen fields of view were identified to genus and their numbers counted. Approximately 10 slides were examined from each sample for phytoplankton genera and relative composition (%) determination from the six sites. Cell counts ranged from 500 to 5000 for each site and tidal level. Identifications to genus were based on Wood (1968), Yama (1973), Cupp (1977), and Vineyard (1979). Identification of taxa to the species level requires electron microscopy and was outside the scope of our study (Round et al. 1990). Genera previously determined to be monospecific in this region were tentatively (see Gallagher 1980, 1982, Medlin et al. 1988) assigned to species (Round et al. 1990, Gilmartin and Revelante 1974).

Community Analysis

Associations among populations were analyzed by Bray-Curtis polar ordination (Gauch 1977 [Ordiflex release B]) with equal weight

TABLE 1

DISTRIBUTION OF PHYTOPLANKTON GENERA IN THE ALA WAI CANAL AT LOW (l), FLOOD (f), AND HIGH (h) TIDES

PHYTOPLANKTON	Site 1			Site 2			Site 3			Site 4			Site 5			Site 6		
Bacillariophyta																		
Achnanthes	l	f	h	l	f	h	l	nd	h	l	f	h	l	ns	h	l	ns	h
Chaetoceros	l	f	h	l	f	h	l	f	h	l	f	h	l	ns	h	l	ns	h
Climacosphenia	l	f	h	l	f	h	l	f	nd	l	f	nd	l	ns	h	l	ns	h
Coscinodiscus	l	f	h	l	nd	h	l	f	h	l	f	nd	l	ns	h	l	ns	h
Cymatopleura	nd	nd	nd	l	nd	nd	l	nd	h	l	nd	nd	nd	ns	h	nd	ns	nd
Epithemia	l	f	h	l	nd	h	l	nd	h	l	f	h	nd	ns	h	nd	ns	h
Grammatophora	l	f	h	l	f	h	nd	f	h	l	f	h	nd	ns	h	nd	ns	h
Licmophora	l	f	h	l	f	h	nd	f	h	l	f	h	nd	ns	h	nd	ns	h
Melosira	l	f	h	l	f	h	l	f	h	l	f	h	nd	ns	h	nd	ns	nd
Navicula	l	f	h	l	f	h	l	f	h	l	f	h	l	ns	h	l	ns	h
Nitzschia	l	f	h	l	f	h	nd	f	h	l	f	h	l	ns	h	l	ns	h
Planktoniella sol	l	f	h	l	nd	h	l	nd	h	l	nd	h	nd	ns	nd	nd	ns	nd
Plagiotropis	l	f	h	l	nd	nd	nd	nd	h	l	nd	h	nd	ns	nd	nd	ns	nd
Pleurosigma	l	f	h	l	nd	h	l	f	h	l	f	h	l	ns	h	l	ns	h
Skeletonema costatum	l	f	h	l	f	h	nd	f	h	l	f	h	l	ns	h	l	ns	h
Surirella	l	nd	nd	l	nd	h	nd	nd	h	l	f	nd	nd	ns	h	nd	ns	nd
Thallassionema	nd	f	h	l	f	h	nd	f	h	l	f	h	nd	ns	h	l	ns	nd
Thalassiothrix	l	f	nd	l	nd	h	nd	f	h	l	nd	h	l	ns	h	nd	ns	nd
Triceratium	l	f	h	nd	nd	nd	l	nd	nd	l	nd	nd	nd	ns	nd	nd	ns	nd
Undellata	l	f	h	l	nd	h	l	nd	h	l	f	nd	l	ns	h	l	ns	h
Pyrrhophyta																		
Amphidinium	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	h	l	ns	h	l	ns	h
Gonyaulax	nd	nd	nd	nd	nd	nd	l	nd	nd	nd	nd	nd	nd	ns	nd	nd	ns	nd
Gymnodinium	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	h	l	ns	h	l	ns	h
Peridinium	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	h	l	ns	h	l	ns	h
Cyanophyta																		
Lyngbya	l	f	h	l	f	h	l	f	h	l	f	h	l	ns	h	l	ns	h
Generic richness	18	18	18	19	10	17	13	12	18	20	14	17	13	ns	20	13	ns	15

nd, not detected; ns, not sampled.

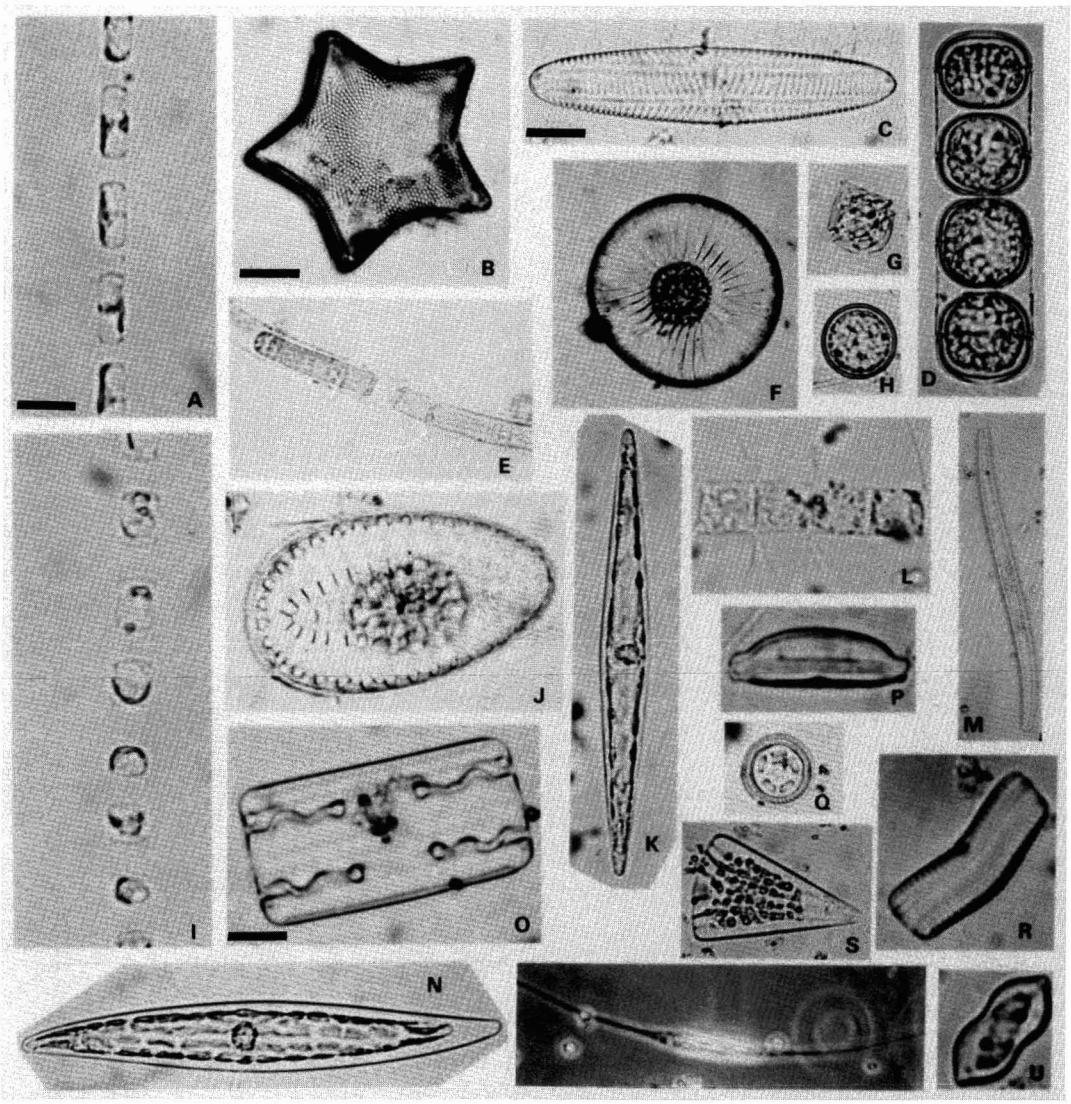

FIGURE 2. Select phytoplankton from the Ala Wai Canal. *A*, *Skeletonema costatum**; *B*, *Triceratium* sp.**; *C*, *Navicula* sp.***; *D*, *Melosira* sp.***; *E*, *Lyngbya* sp.***; *F*, *Planktoniella sol***; *G*, *Gonyaulax* sp.***; *H*, *Coscinodiscus* sp.***; *I*, *Skeletonema costatum**; *J*, *Surirella* sp.***; *K*, *Navicula* sp.***; *L*, *Chaetoceros* sp.*; *M*, *Pleurosigma* sp.**; *N*, Pleurosigmoid sp.***; *O*, *Grammatophora* sp.****; *P*, *Epithemia* sp.****; *Q*, *Coscinodiscus* sp.***; *R*, *Achnanthes* sp.****; *S*, *Licmophora* sp.***; *T*, *Nitzschia* sp.**; *U*, *Cymatopleura* sp.****. *, scale bar = 8.2 μm; **, scale bar = 32.6 μm; ***, scale bar = 16.3 μm; ****, scale bar = 6.5 μm.

given to each taxon (Mueller-Dombois and Ellenberg 1974). The homogeneity (evenness) of populations between sites and tidal stages was analyzed with comparisons of $J' = H'/H'_{max}$ (Pielou 1966).

RESULTS

Twenty genera of planktonic diatoms, four genera of dinoflagellates, and one genus of blue-green bacteria (cyanophyte) were identi-

fied from net phytoplankton samples of the six sites in the Ala Wai Canal (Table 1, Figure 2). With the exceptions of three taxa, *Planktoniella sol* (Wallich) Schutt, *Triceratium*, and *Plagiotropis*, all of the diatom genera were found at each site during at least one point of the tidal cycle (Table 1). *Planktoniella sol*, *Triceratium*, and *Plagiotropis*, as well as *Cymatopleura*, composed a greater relative percentage of the phytoplankton sampled at site 1 compared with that at sites 2–6 (Figure 3). The taxa *Achnanthes*, *Undellata*, *Climacosphenia*, *Coscinodiscus*, *Pleurosigma*, *Navicula*, *Nitzschia*, and *Skeletonema* were abundant at all sites and all tidal levels. *Lyngbya* was found at all sites regardless of tidal stage and occurred in low relative densities.

Sites 4, 5, and 6 were the only locations where the dinoflagellates *Amphidinium*, *Gymnodinium*, and *Peridinium* were detected. The dominance of these dinoflagellates at sites 5 and 6 clearly differentiated the head of the canal from more seaward sites on the basis of a Bray-Curtis ordination (Figure 4). This cluster analysis also revealed the similarity between site 2 at all three tidal levels, site 3 at flood and high tides, and site 4 at high and site 1 at low tide (Figure 4). Site 1 at high and flood tides as well as site 4 at low and flood tides were peripheral to the outer estuarine cluster (Figure 4). The phytoplankton at site 1 during high and flood tides had a greater percentage of rare taxa such as *P. sol*, *Triceratium*, *Plagiotropis*, and *Cymatopleura* (Figure 3). In contrast, site 4 at low and flood tides had diatoms that overlapped between inner estuarine sites and sites 5 and 6 (Figure 4). The apparent clustering of site 1 at high and flood tides with site 4 at low and flood tides reflected their dissimilarity to other sites at any tidal level and was not the result of their inherent similarity. Dinoflagellates were observed at site 4 only during high tide (Table 1).

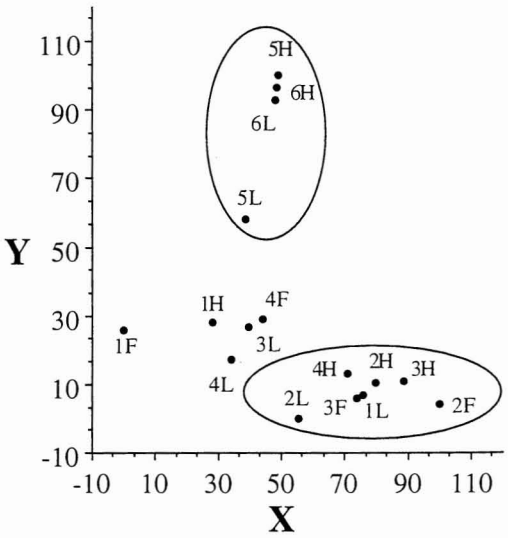

FIGURE 4. Bray-Curtis ordination of phytoplankton populations at sites 1–6 at low (L), flood (F), and high (H) tide. Associations fitted by eye.

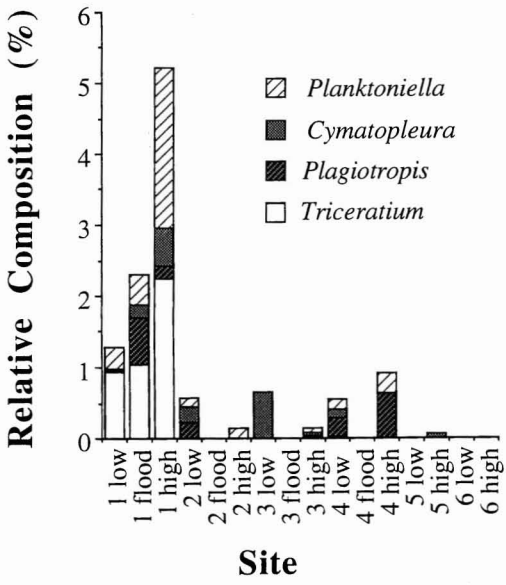

FIGURE 3. Relative composition (%) of four diatom genera within the Ala Wai Canal.

The generic richness observed at each site ranged between 10 and 20 for each sampling interval (Table 1). All areas were judged equally rich; no spatial or temporal trend in net phytoplankton richness was discernible over the 4 days and one tidal cycle of sampling. Comparisons of the homogeneity among the distribution of net phytoplankton genera as indicated by J' (Pielou 1966) re-

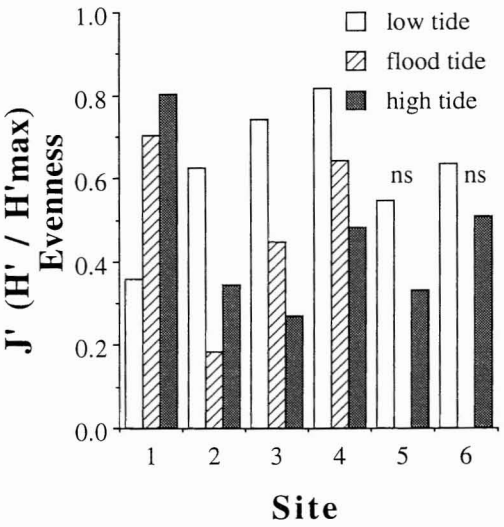

FIGURE 5. Evenness index, $J' = (H'/H'_{max})$ (Pielou 1966), for phytoplankton populations at sites 1–6 at three tidal levels. ns, not sampled; $n = 3$. H'_{max} based on site/tide specific generic richness in Table 1.

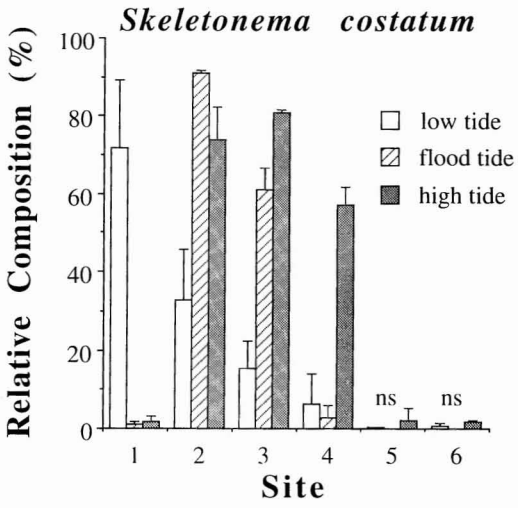

FIGURE 6. Relative composition (%) of *Skeletonema costatum* at sites 1–6 at three tidal levels. ns, not sampled; error bars = standard deviation of the mean; $n = 3$.

vealed both spatial and temporal changes in the relative distribution of net phytoplankton (Figure 5). With the influx of high-tide waters, the homogeneity increased at site 1, whereas evenness dropped at site 2 with the flood tide and increased again with the high tide. Sites 3, 4, 5, and 6 all decreased in evenness with the incoming tide (Figure 5). The differential change in homogeneity at sites 1–4 was inversely proportional to the distribution of *Skeletonema costatum* (Greville) Cleve.

Diatoms of the species *S. costatum* constituted greater than 60% of the observed net phytoplankton taxa at sites 1–4 for one or more tidal phases (Figure 6). The relative percentage composition of *S. costatum* changed at sites 1–4 over the tidal cycle (Figure 6). The relative abundance of *S. costatum* decreased 20-fold from low to high tide at site 1. At site 2, the peak relative abundance of 93% was detected during flood tide (Figure 6). At sites 3 and 4, the relative abundance peaked at 81 and 57%, respectively, with the greatest influx of marine water at high tide (Figure 6). With tidal cycling a more evenly distributed phytoplankton population replaced *S. costatum* as that population moved with tidal currents (Figure 5).

Nauplius larvae, copepods, and flatworm and polychaete larvae were the principal zooplankton detected in the canal by our sampling scheme. The relative composition indicated that zooplankton made up less than 5% of the net plankton community at sites 1, 2, 3, 5, and 6 at all tidal levels. A consistent peak in abundance (5.5 to 11%) was associated with site 4 regardless of tide level (data not shown).

DISCUSSION

The subsurface waters of the Ala Wai Canal contain a diverse assemblage of net phytoplankton consisting of a minimum of 20 diatom, one blue-green bacteria, and four dinoflagellate genera and at least a comparable number of species, potentially more. Two regions of the canal can be distinguished by their net phytoplankton components. The seaward portion (sites 1–4) of the canal was composed principally of diatoms, with few to no dinoflagellates in the regions sampled.

Based on their distribution within the canal, the diatoms of this region were of two classes. The taxa *P. sol*, *Triceratium*, *Plagiotropis*, and *Cymatopleura* typically were not present in and may be intolerant of physical conditions found deeper in the canal (Figure 3). Taxa including *Achnanthes*, *Undellata*, *Pleurosigma*, *Navicula*, *Nitzschia*, and *S. costatum* were detected throughout the canal and appear to tolerate its variable conditions (Table 1). The sediment berm at the Mānoa-Pālolo Stream outfall was associated with the second distinct net phytoplankton assemblage within the canal. Dinoflagellate distribution was strongly associated with basin waters at the head of the canal (Table 1). Water in that region differs from channel and sill waters (sites 1–4) by (1) restricted water circulation, (2) higher water temperature, and (3) decreased O_2 concentrations (Gonzalez 1971). The relative percentage composition of the cyanobacterium *Lyngbya* appeared to be unaffected by the changing physical parameters from the head to the mouth of the canal (Table 1).

Tidal flux caused movement of phytoplankton within the seawardmost portion of the canal. Two community features, population affinity and homogeneity, indicated that the tidal cycle shifts the net phytoplankton distribution with its ebb and flow. The population affinities as indicated by Bray-Curtis ordination (Figure 4) of sites 1 at low, 2 at low and flood, 3 at flood and high, and 4 at high tide suggest a tidally controlled movement of phytoplankton. Tidal migration of diatoms occurred from the mouth of the canal at ebbmost tide to inner canal regions (sites 3 and 4) at high tide. Second, the change in the homogeneity within sites at different tidal levels (Figure 5) was attributable directly to the shift in one community component, *S. costatum* (Figure 6). The relative percentage composition of *S. costatum* indicated movement between sites 1 at low and 4 at high tide. Results of the evenness index indicated that the net phytoplankton distribution is more similar at sites 5 and 6 between high and low tides than at sites on the seaward side of the sediment berm (Figure 5). The distribution of dinoflagellates and diatoms from the head to the mouth of the canal and apparent tidal migration of diatoms was not attributable to site or taxon-specific grazing by zooplankton. Zooplankton are rare ($\leq 5\%$) at most sites, and their distribution does not conform with either of these patterns.

Management of the Ala Wai Canal has proven problematic to the city of Honolulu, with concerns summarized by Laws et al. (1993) ranging from hypereutrophication (Harris 1975, Laws et al. 1993), sedimentation (Gonzalez 1971), heavy metals (Louma 1974, Department of Health 1980), and pesticides (Shultz 1971) to pathogens (Cox 1969). Laws et al. (1993) discussed the potential effects of pumping in seawater at the head of the canal as proposed by Cox and Miller (1976) on the water clarity, phytoplankton densities, photosynthetic and respiration rates, oxygen concentrations in the bottom waters, subsequent effects on upper sediment redox potential, and sedimentation within the canal. In addition to these changes, the phytoplankton population structure at regions near the head of the canal may be markedly altered. Higher flushing rates have been proposed as the cause for the diatom-dominated community found in the seaward portions of the canal (Harris 1975). The community structure revealed in our study suggests that flushing the canal at its head will redistribute the dinoflagellate populations into regions for which they are less well suited and alter the physical environment to favor a diatom-dominated assemblage.

Anthropogenic modification of wetlands in the Hawaiian Islands has been continuous since early settlement. Water has been diverted from many mountain streams to irrigate sugarcane, pineapple, rice, and taro (Fungladda et al. 1982). Currently, one-third of the streams in Hawai'i are diverted and one-fifth are channelized, including most of O'ahu's streams (State of Hawai'i and National Park Service 1990). Assessments of estuarine algal flora are scant (see Abbott 1947), and distributional data are lacking for phytoplankton. Our study has provided detailed reaffirmation of the overall distribution of phytoplankton divisions in the Ala

Wai Canal (Laws et al. 1994), but by establishing the identity of phytoplankton genera, any impact because of canal modification can be assessed with greater insight and precision.

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